



# Analysis of Electromagnetic Noise From Switching Power Modules Using Wide Band Gap Semiconductors

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# Analysis of Electromagnetic Noise From Switching Power Modules Using Wide Band Gap Semiconductors

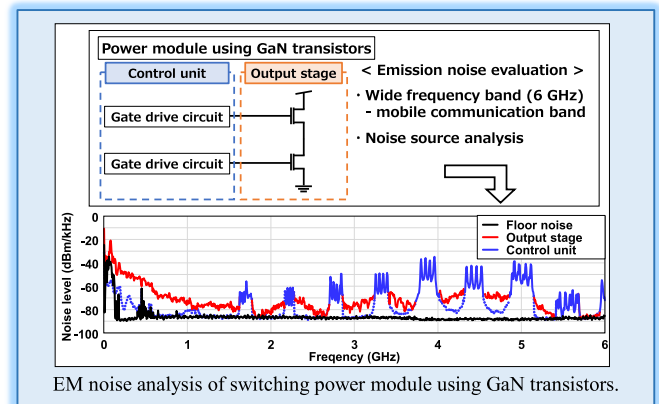
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**Abstract**—Wide band gap (WBG) semiconductors, such as gallium nitride (GaN), have become popular among switching power modules. In pursuing power conversion efficiency, power module's high-speed and high-power operation leads to electromagnetic (EM) noise in a very wide frequency range, potentially interfering with nearby wireless communications [e.g., long-term evolution (LTE)]. This letter analyzes the source of EM noise from the power modules using GaN transistors in half-bridge circuits. EM noise was clearly observed in the proximity of power modules and attributed to two primary sources in the frequency range of interest up to 6 GHz: 1) the periodical switching operation of GaN transistors in the output stage and 2) the logic operation of complementary metal–oxide–semiconductor digital circuits to control gate drivers, in the lower and upper side of frequencies, respectively. Measurements analyzed the EM noise characteristics at different probing locations over the assembly of two GaN power modules as well as in different operating conditions by strategically supplying source signals. The influence of EM noise on LTE receiver performance is evaluated with wireless system-level simulation and related to the degradation of its minimum receivable input power.

**Index Terms**—DC–DC power conversion, electromagnetic interference (EMI), mobile communication, noise measurements, power semiconductor devices.

## I. INTRODUCTION

WIDE band gap (WBG) semiconductors, such as gallium nitride (GaN), have become more widely adopted into power supply electronics in comparison to traditional silicon (Si) devices [1]. WBG semiconductors (e.g., GaN) have superior material properties compared to Si, and their use



in the output stage of power supply enables power device operation at higher temperatures, higher voltages, and faster switching speeds, in comparison to traditional Si [2], [3]. Therefore, WBG semiconductors make power modules more efficient and compact and become widely adopted among a variety of applications (e.g., the Internet of Things, automotive electronics, robotics, and so on) [4]. However, there is an inevitable tradeoff between power efficiency and noise emission, where the faster switching and the higher voltage for the lower energy loss conversely increase the magnitude of power noise due to periodical switching currents flowing through power semiconductors [5], [6], [7]. This also brings about

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## Take-Home Messages:

- EM noise of GaN power modules spreads over 6 GHz with the noise power level that is influential to nearby wireless receiver channels. The LTE bands at 800 MHz and 4.5 GHz are exemplified for the degradation of the minimum receivable power.
- EM noise from the GaN output stage is observed in the lower side of the frequency, typically within 1.5 GHz, and the noise power is highly dependent on the switching frequency in the order of 100 kHz and 1 MHz.
- EM noise from the gate drivers and controllers is observed in the higher counterpart due to the large harmonic index to the base clock frequency of CMOS digital circuits at 100 MHz or even higher.

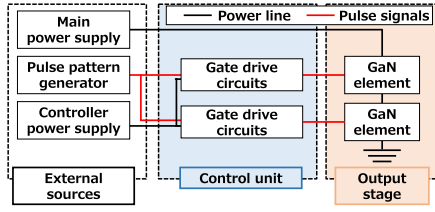


Fig. 1. Configuration diagram of the GaN-based power modules and experimental setup.

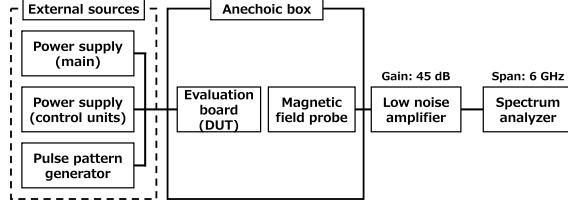


Fig. 2. Measurement setup in wide frequency range.

near-field electromagnetic interference (EMI) problems among electronic modules in proximate placements. The adoption of such high energy-efficient power converters in electronic systems expedites the maturity of power modules with the WBG devices, such as GaN and Si carbide (SiC), while necessitates the EM compatibility (EMC) measurements in the frequency range wider than ever. Traditionally, the EMC requirements of power modules are generally defined in the frequency range up to 1 GHz [8]. According to our previous study on a commercial wireless power transmission (WPT) system adopting GaN power modules with a high wattage capacity (e.g., 7 kW), the influence of EM noise on the sensitivity of wireless receivers in serving LTE is not negligible in nearby locations with a few meters distance [9]. The EMI between WBG semiconductors and wireless communication systems has become problematic universally among IoT devices. This letter presents an EM noise analysis of GaN-based power modules in the frequency range (up to 6 GHz) for mobile communications.

## II. EM NOISE IN GAN-BASED POWER MODULES

### A. GaN-Based Power Modules

In this study, we prepare two power modules, GaN modules A and B; both consist of GaN-based half-bridge circuits and isolated gate drive circuits using CMOS devices. While the block diagram of Fig. 1 is common to both modules, the assembly structures are different according to respective design parameters as listed in Table I. The output stage is populated with two GaN-based discrete transistors and configured as a half-bridge circuit. The control unit mainly includes gate drive circuits. An auxiliary power source at 12 V externally powers on-board voltage regulators to produce 5 and 12 V for each component on the control unit. Another main supply defines the operated voltage level of GaN transistors in the half-bridge power stage. The pair of GaN transistors is driven by complementary pulse signals (noninverted and inverted) generated by the gate drive circuits. The frequency and duty ratio of input pulse signals are set by a pulse pattern

TABLE I  
SPECIFICATION OF TWO POWER MODULES USING GAN TRANSISTORS

	GaN module A	GaN module B
Circuitry	Half-bridge	Half-bridge
Isolated / Non-isolated	Isolated	Isolated
Max. output voltage	650 V	450 V
Max. output current	60 A	35 A
Max. operating freq.	10 MHz	3 MHz

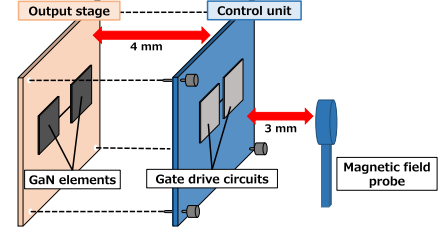


Fig. 3. Identification of EM noise source by external source signals (GaN module A).

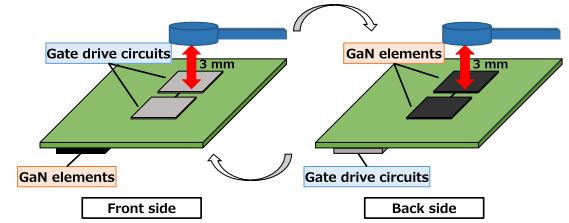


Fig. 4. Identification of EM noise source by probe position (GaN module B).

generator. In this work, the parameters of external source signals were configured as follows: 1) the main power supply: 0 and 12 V; 2) the pulse frequency: 100 kHz and 1 MHz; and 3) the pulse duty ratio: 50%.

### B. EM Noise Sources on Power Modules

We use a magnetic field probe to capture the near-field EM noise to the device under test (DUT), as shown in Fig. 2. Everything is placed inside an anechoic box to eliminate the environmental noise. This measurement setup was extended from the high sensitivity measurement system of our previous work detailed in [10]. The frequency range of interest is 6 GHz to cover the wireless communication bands for LTE and fifth-generation (5G) wireless systems. The following measurements were performed with no load at the output stage of a power module for simplicity; however, it was initially confirmed that the EM noise components in the bands of interest above 500 MHz were insensitive to the sizes of resistive loads.

The EM sources are experimentally analyzed on the respective DUTs, as shown in Figs. 3 and 4, with different operating conditions by strategically supplying source signals, and also at different probing points over the assembly of GaN modules. The power supply module was operated in two different states by varying the settings of the external signal source. One was set as the basic operating state, with mains: 12 V, operating frequency: 100 kHz, and duty ratio: 50%, with all circuits driven. Therefore, the radiated noise generated from the GaN device and the control unit was measured. The other is with the main power supply set to 0 V and the switching

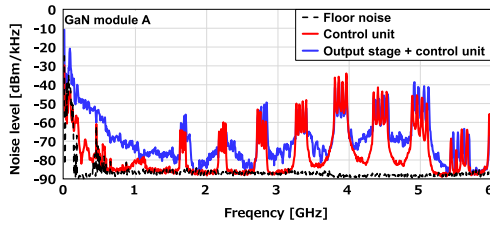


Fig. 5. Frequency characteristics of EM noise from the output stage and the control unit in GaN module A.

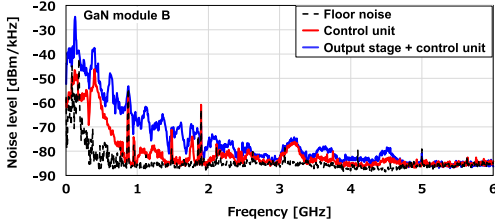


Fig. 6. Frequency characteristics of EM noise from the output stage and the control unit in GaN module B.

operation of the GaN device is stopped. In this case, the only radiated noise observed is the noise component generated by the control unit. Thus, the source of radiated noise in the power supply module was analyzed by changing the circuit operation state and comparing the observed radiated noise components. The following experimental results (Figs. 5 and 6) show the results when the output stage is operating (including EM noise from the output stage and the control unit, as shown by the blue line) and not operating (excluding EM noise from the output stage, as shown by the red line).

The probing point was set as shown in Fig. 3 for EM measurements of GaN module A. Once the probe is set on the front side of the control unit with an air distance of 3 mm, the total distance becomes 7 mm from the output stage in its stacked-board assembly structure. The typical EM noise is measured by a spectrum analyzer, as shown in Fig. 5. EM noise from the output stage is observed below 1.5 GHz, which is dominated by the harmonic components to the switching frequency given to the GaN transistors set by the pulse generator.

In GaN module B, the frequency characteristics of EM noise from the output stage and the control unit were measured from the respective side of the double-sided assembly structure. EM noise from the output stage was dominantly observed below 2 GHz, as given in Fig. 6.

It is of interest to note commonly from the measured frequency components on the modules A and B that the EM noise sources of power modules are primarily divided into two components: 1) the periodical switching operation of GaN transistors in the output unit and 2) the logic operation of CMOS digital circuits to control gate drivers on the control unit. We generally find that the EM noise from the output stage dominates the lower frequency side, while the others from the control circuit are more likely present at the upper frequency side. The crossover frequency is from 1 to 2 GHz, depending on the design parameters.

The control unit emanates the equally spaced spurious units, more particularly in the module A. The fundamental frequency

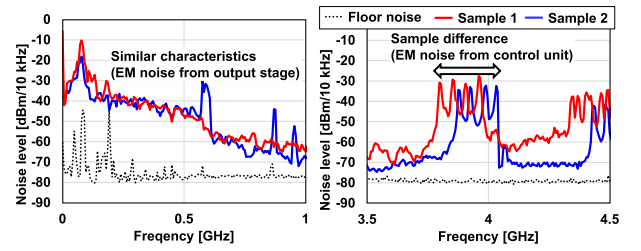


Fig. 7. Uniqueness of the EM noise components from GaN module A.

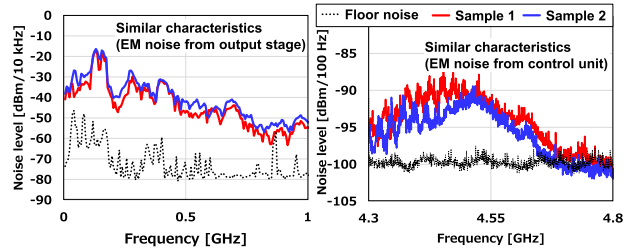


Fig. 8. Uniqueness of the EM noise components from GaN module B.

of the four spurs from the control units was 550-MHz band, and their harmonics were observed at 6 GHz even when the pulse signals were not supplied. The transformer coil in the isolation part and the undervoltage lockout device (UVLO) are presumed to be the sources of the EM noise since they operate independently of the pulse signals.

The uniqueness of such EM noise components from the output and control units was also evaluated. The EM noise was measured among two samples, for each module A and B, as compared in Figs. 7 and 8, respectively. In general, the repeatability of measurements is confirmed. The EM noise below 1 GHz dominated by the output unit is not different among the two samples, as seen in both modules. On the other hand, the four consecutive spurs apparently seen in the control unit regime of the module A are almost equivalent but in different positions on the frequency axis among the samples, as magnified in the 4-GHz band. The frequency components in the same regime of the module B exhibit slight differences among the samples.

In summary, EM noise generated by the control unit is independent of the operating conditions of the power supply module while dependent on the inherent characteristics of circuit structures (e.g., ULVO). This requires EM noise evaluation to be executed for a given product and EMI countermeasures to be tailored thereof.

### III. EM NOISE CHARACTERISTICS AND INTERFERENCE

#### A. EM Noise in Different Operating Conditions

EM noise for the different switching frequencies of 100 kHz and 1 MHz given to the output unit is measured as in Figs. 9 and 10, respectively. EM noise enlarges around 20 dB in magnitude in the whole 6-GHz band as commonly observed among both modules. The magnified plots in the 2-GHz band, dominated mainly by the output stage and often used in wireless communication, are given in Fig. 11. The spurious components regularly space each other with the respective

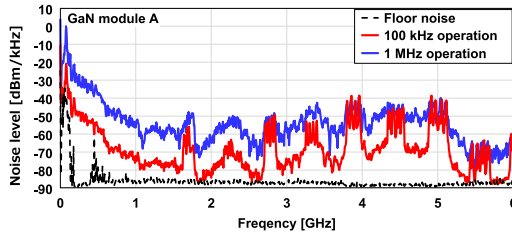


Fig. 9. Operating frequency dependence (100 kHz and 1 MHz) of EM noise characteristics in GaN module A.

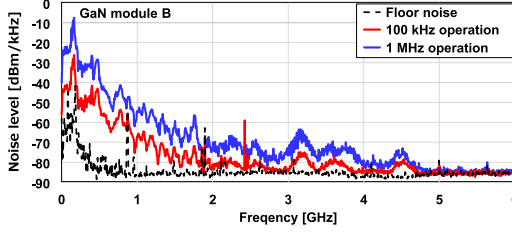


Fig. 10. Operating frequency dependence (100 kHz and 1 MHz) of EM noise characteristics in GaN module B.

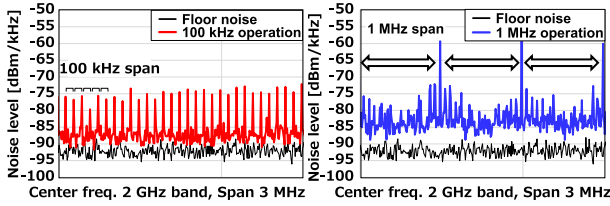


Fig. 11. Spurious components from the output stage operating at 100 kHz and 1 MHz.

operating frequency. On the other hand, the noise level from the control unit was not changed since their internal clocking frequency is independent. From these results, the operating frequency of power modules critically affects the EM noise frequency components.

### B. EM Noise Interference on Cellular Communications

We analyzed the interference of EM noise on cellular wireless communications through wireless system-level simulation based on the recorded EM noise data [9]. The simulation relies on the models with RF parameters derived from receiver physical circuits in cellular communication and analyzes the impact of EM noise on the minimum sensitivity of the receiver. There is some error in the antenna gain compared to the actual one. The data throughput of downlink signals, the carrier signal from a base station to user equipment (UE) in a cellular network system, is calculated, considering the noise level at the front end of a receiver. The minimum receivable signal power density  $P_{\min}$ , is derived at 95% of the data throughput, which is defined in the third-generation partnership project (3GPP) [11].

EM noise from GaN module A in the bands of 800 MHz and 4.5 GHz were measured and captured, as in Section II, and then given to the wireless system simulation assuming LTE and 5G cellular channels. The  $P_{\min}$  was degraded for 3 and 16 dB, in response to EM noise dominated by the output stage in 800 MHz and that by the control unit in 4.5 GHz,

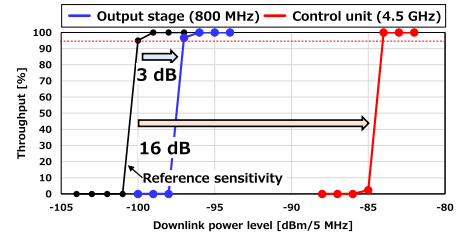


Fig. 12. Impact of EM noise from the output stage and the control unit on cellular communications with 100-kHz switching.

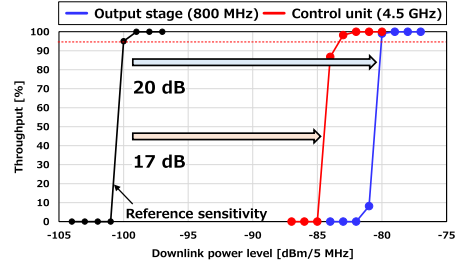


Fig. 13. Impact of EM noise from the output stage and the control unit on cellular communications with 1-MHz switching.

respectively, as shown in Fig. 12. The simulation framework and RF models are detailed in [9].

In the case of high switching operation at 1 MHz, the  $P_{\min}$  becomes more degraded by 17 dB in the 800-MHz band, as is compared to the case in 100-kHz switching operation. On the other hand, the impact by the control unit was almost unchanged in the 4.5-GHz band, as shown in Fig. 13. The wireless system-level simulation relates the EM noise to the potential interference on wireless systems of interest.

## IV. CONCLUSION

A power module using GaN transistors at its output stage emanates the EM noise up to 6 GHz that covers the entire frequency bands of sub-6 GHz for LTE and 5G. EM noise power is not negligible for EMI in the nearby location of wireless modules. The expedited adoption of WBG transistors for energy efficient and area compact IoT devices makes the problem more universal and the countermeasures necessary to mitigate EM noise interference.

There are two primary noise sources: 1) an output stage using WBG power transistors with periodical switching and 2) the control and gate driver stages with CMOS digital circuits with clock signal externally given or even internally generated. EM noise from the output stage circuit using GaN elements was dominantly observed below 1.5 GHz in the setup of this work. In addition, the frequency range and the noise level of the EM noise based on GaN transistors depend on the operating frequency of switching power modules. EM noise from the control circuit was mainly observed above 1.5 GHz. However, this noise constantly emanated in the 6-GHz band regardless of the behavior of GaN transistors. These observations are commonly confirmed among the two power modules using GaN in the different assembly styles.

The targets of the noise countermeasures for wireless communications are not only output stage circuits but also control circuits in switching modules. The necessary level of noise



reduction can be estimated through wireless system-level simulation that combines the measured EM noise and behavioral models of wireless transceiver (radio-frequency) circuits as demonstrated.

Further study will be continued for a more generalized EM noise analysis over power modules in different WBG transistors and diversified power circuit topologies.

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#### REFERENCES

- [1] H. Li *et al.*, "Design of a 10 kW GaN-based high power density three-phase inverter," in *Proc. IEEE Energy Conver. Congr. Expo. (ECCE)*, Milwaukee, WI, USA, 2016, pp. 1–8, doi: [10.1109/ECCE.2016.7855019](https://doi.org/10.1109/ECCE.2016.7855019).
- [2] J. Millán, P. Godignon, X. Perpiñà, A. Pérez-Tomás, and J. Rebollo, "A survey of wide bandgap power semiconductor devices," *IEEE Trans. Power Electron.*, vol. 29, no. 5, pp. 2155–2163, May 2014, doi: [10.1109/TPEL.2013.2268900](https://doi.org/10.1109/TPEL.2013.2268900).
- [3] R. S. Pengelly, S. M. Wood, J. W. Milligan, S. T. Sheppard, and W. L. Pribble, "A review of GaN on SiC high electron-mobility power transistors and MMICs," *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 6, pp. 1764–1783, Jun. 2012, doi: [10.1109/TMTT.2012.2187535](https://doi.org/10.1109/TMTT.2012.2187535).
- [4] J. M. Martínez-heredia, F. Colodro, J. L. Mora-Jiménez, A. Remujo, J. Soriano, and S. Esteban, "Development of GaN technology-based DC/DC converter for hybrid UAV," *IEEE Access*, vol. 8, pp. 88014–88025, 2020.
- [5] B. Liu, R. Ren, Z. Zhang, B. Guo, F. Wang, and D. Costinett, "Impacts of high frequency, high di/dt, dv/dt environment on sensing quality of GaN-based converters and their mitigation," *CPSS Trans. Power Electron. Appl.*, vol. 3, no. 4, pp. 301–312, Dec. 2018.
- [6] Y. Zhang, S. Wang, and Y. Chu, "Analysis and comparison of the radiated electromagnetic interference generated by power converters with Si MOSFETs and GaN HEMTs," *IEEE Trans. Power Electron.*, vol. 35, no. 8, pp. 8050–8062, Aug. 2020, doi: [10.1109/TPEL.2020.2972342](https://doi.org/10.1109/TPEL.2020.2972342).
- [7] T. Ibuchi and T. Funaki, "A comparative study on conducted noise characteristics of SiC and GaN power transistor," in *Proc. Int. Symp. EMC EUROPE*, Wrocław, Poland, 2016, pp. 193–198, doi: [10.1109/EMCEurope.2016.7739169](https://doi.org/10.1109/EMCEurope.2016.7739169).
- [8] CISPR11: 2015, "Industrial, scientific and medical equipment - Radio-frequency disturbance characteristics—Limits and methods of measurement," Standards Australia, Sydney, NSW, Australia, Rep. AS CISPR 11:2017, 2015.
- [9] M. Nagata *et al.*, "Evaluation of near-field undesired radio waves from semiconductor switching circuits," in *Proc. Int. Symp. EMC EUROPE*, Barcelona, Spain, 2019, pp. 866–869, doi: [10.1109/EMCEurope.2019.8871554](https://doi.org/10.1109/EMCEurope.2019.8871554).
- [10] K. Watanabe *et al.*, "Evaluation of undesired radio waves below −170 dBm/Hz from semiconductor switching devices for impact on wireless communications," *IEEE Lett. Electromagn. Compatibil. Pract. Appl.*, vol. 1, no. 3, pp. 72–76, Sep. 2019, doi: [10.1109/LEMCPA.2020.2976990](https://doi.org/10.1109/LEMCPA.2020.2976990).
- [11] "LTE; evolved universal terrestrial radio access; user equipment (UE) radio transmission and reception," 3GPP, Sophia Antipolis, France, TS 36.101 version 8.4.0 Release 8, Jan. 2009.